MAGNETIC FIELDS IN THE MILKY WAY AND OTHER SPIRAL GALAXIES

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Abstract

The average strength of the *total* magnetic field in the Milky Way, derived from radio synchrotron data under the energy equipartition assumption, is 6μG locally and $\simeq 10\mu$G at 3 kpc Galactic radius. Optical and synchrotron polarization data yield a strength of the local *regular* field of $\simeq 4\mu$G (an upper limit if anisotropic fields are present), while pulsar rotation measures give $\simeq 1.5\mu$G (a lower limit if small-scale fluctuations in regular field strength and in thermal electron density are anticorrelated). In spiral arms of external galaxies, the total [regular] field strength is up to $\simeq 35\mu$G [$\simeq 15\mu$G]. In nuclear starburst regions the total field reaches $\simeq 50\mu$G. – – Little is known about the global field structure in the Milky Way. The local regular field may be part of a "magnetic arm" between the optical arms, a feature that is known from other spiral galaxies. Unlike external galaxies, rotation measure data indicate several global field reversals in the Milky Way, but some of these could be due to field distortions. The Galaxy is surrounded by a thick radio disk of similar extent as around many edge-on spiral galaxies. While the regular field of the local disk is of even symmetry with respect to the plane (quadrupole), the regular field in the inner Galaxy or in the halo may be of dipole type. The Galactic center region hosts highly regular fields of up to milligauss strength which are oriented perpendicular to the plane.

Keywords: Radio continuum, polarization, magnetic fields, interstellar medium

1. Motivation

Magnetic fields are a major agent in the interstellar medium. They contribute significantly to the total pressure which balances the ISM against gravitation. They affect the gas flows in spiral arms and around bars. Magnetic fields are essential for the onset of star formation as they enable the removal of angular momentum from the protostellar cloud during its collapse. MHD turbulence distributes energy from supernova explosions within the ISM. Magnetic recon-

nection is a possible heating source for the ISM and halo gas. Magnetic fields also control the density and distribution of cosmic rays in the ISM.

2. Observing magnetic fields

Polarized emission at optical, infrared, submillimeter and radio wavelengths is the clue to interstellar magnetic fields. Radio continuum emission at centimeter wavelengths, emitted by cosmic-ray electrons in the interstellar medium, by pulsars and by background quasars, has higher degrees of polarization than in the other spectral ranges and provides the most extensive and reliable information on large-scale interstellar magnetic fields in our Galaxy (Heiles 1996, Han et al. 1999a) and about 70 external galaxies (see list in Beck 2000). The observable degree of polarization is reduced by the contribution of unpolarized thermal emission which may dominate in star-forming regions, by Faraday depolarization (Sokoloff et al. 1998) and by geometrical depolarization within the beam. The orientation of polarization vectors is changed in a magneto-ionic medium by *Faraday rotation* which is generally small below about $\lambda 6$ cm so that the $\mathbf{B}$–vectors (i.e. the observed $\mathbf{E}$–vectors rotated by $90°$) directly trace the *orientation* of the regular (or anisotropic) fields in the sky plane.

Polarization angles are ambiguous by $\pm 180°$ and hence insensitive to field reversals. Compression or stretching of turbulent fields generates incoherent anisotropic fields which reverse direction frequently within the telescope beam, so that Faraday rotation is small while the degree of polarization can be high. Strong Faraday rotation is a signature of coherent regular fields, and the sense of rotation reveals the *sign* of the field.

3. Magnetic field strengths

The average strength of the total $\langle B_{\mathrm{t},\perp} \rangle$ and the resolved regular field $\langle B_{\mathrm{reg},\perp} \rangle$ in the plane of the sky can be derived from the total and polarized radio synchrotron intensity, respectively, if energy-density equipartition between cosmic rays and magnetic fields is assumed (see Beck et al. 1996 for details).

In our Galaxy the accuracy of the equipartition assumption can be tested, because we have independent information about the local cosmic-ray energy density from in-situ measurements and about their radial distribution from γ-ray data. Combination with the radio synchrotron data yields a local strength of the total field $\langle B_{\mathrm{t}} \rangle$ of 6μG (Strong et al. 2000), the same value as derived from energy equipartition (Berkhuijsen, in Beck 2001). Even the radial scale length of the equipartition field of $\simeq 12$ kpc (Fig. 1) is similar to that in Strong et al. (2000). Near the Galactic center the field strength reaches 1 mG (Reich 1994, Yusef-Zadeh et al. 1996).

The mean equipartition strength of the total field for a sample of 74 spiral galaxies (Niklas 1995) is $\langle B_{\mathrm{t}} \rangle \simeq 9\mu$G. Radio-faint galaxies like M 31 and

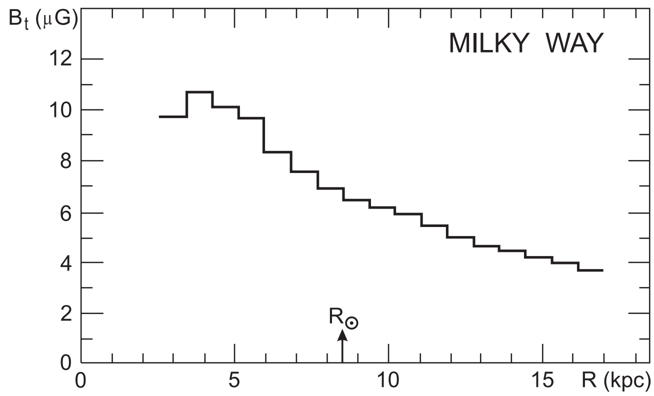

Figure 1. Strength of the total magnetic field in the Galaxy, averaged from the deconvolved surface brightness of the synchrotron emission at 408 MHz (Beuermann et al. 1985), assuming energy equipartition between magnetic field and cosmic ray energy densities. The accuracy is about 30%. The Sun is assumed to be located at R=8.5 kpc. (From Berkhuijsen, in Beck 2001)

M 33 have $\langle B_{\rm t}\rangle \simeq 6\mu$G, while $\simeq 15\mu$G is typical for grand-design galaxies like M 51, M 83 and NGC 6946. In the prominent spiral arms of M 51 the total field strength is 30–35μG (Fletcher et al., this volume). Nuclear starburst regions host fields up to $\simeq 50\mu$G strength (Klein et al. 1988, Beck et al. 1999).

Synchrotron polarization observations in the local Galaxy imply a ratio of regular to total field strengths of $< B_{\rm reg}/B_{\rm t} >\simeq 0.6$ (Berkhuijsen 1971, Brouw & Spoelstra 1976, Heiles 1996). The total radio emission along the local spiral arm requires that $< B_{\rm reg}/B_{\rm t} >$=0.6–0.7 (Phillipps et al. 1981). For $\langle B_{\rm t}\rangle = 6 \pm 2\,\mu$G these results give $4 \pm 1\,\mu$G for the local regular field component. Note that equipartition values for $< B_{\rm reg} >$ may overestimate the strength of the coherent regular field if reversals or anisotropic turbulent fields are present.

Rotation measure and dispersion measure data of pulsars give an average strength of the local regular field of $< B_{\rm reg} >= 1.4 \pm 0.2\mu$G (Rand & Lyne 1994, Han & Qiao 1994, Indrani & Deshpande 1998), less than the equipartition estimate. $< B_{\rm reg} >$ derived from pulsar data is underestimated if small-scale fluctuations in field strength and in electron density are anticorrelated, as expected for local pressure equilibrium (Beck et al. 2003). In the inner Norma arm, the average strength of the regular field is $4.4 \pm 0.9\mu$G (Han et al. 2002).

The strength of regular fields $B_{\rm reg}$ in spiral galaxies (observed with a spatial resolution of a few 100 pc) is typically 1–5μG. Exceptionally strong regular fields are detected in the interarm region of NGC 6946 of up to $\simeq 13\mu$G (Beck & Hoernes 1996, see Fig. 3)) and $\simeq 15\mu$G at the inner edge of the inner spiral arms in M 51 (Fletcher, this volume).

In spiral arms of external galaxies the regular field is generally weaker and the tangled (unresolved) field is stronger due to turbulent gas motion in star-forming regions and the expansion of supernova remnants. In interarm regions the regular field is generally stronger than the tangled field.

4. Energy densities in the ISM

The relative importance of various competing forces in the interstellar medium can be estimated by comparing the corresponding energy densities. In the local Milky Way, the energy densities of turbulent gas motions, cosmic rays, and magnetic fields are similar (Boulares & Cox 1990). Global studies are possible in external galaxies like NGC 6946 (Fig. 2). The energy density of the total equipartition magnetic field ($B_{\rm t}^2/8\pi$) is derived from the map of synchrotron emission of Walsh et al. (2002), the thermal energy density ($\frac{3}{2}\langle n_{\rm e}\rangle kT$) of the warm ionized gas ($T \simeq 10^4$ K) from the map of thermal radio emission I_{th} of Walsh et al., using a constant volume filling factor of 5% (see however Mitra et al., this volume), and the thermal energy density of the total neutral gas (molecular + atomic) from the CO map of Walsh et al. and the HI map of Kamphuis & Sancisi (1993), assuming for simplicity a constant scale height of the disk of 100 pc and $T \simeq 50$ K. For the kinetic energy density ($\frac{1}{2}\rho v^2$) of the turbulent motion of the total neutral gas the turbulent velocity of the neutral gas is assumed to be $v_{\rm turb} = 7$ km/s, as for the neutral gas in our Galaxy (Boulares & Cox 1990, Kalberla & Kerp 1998).

According to Fig. 2 the energy density of the ionized gas E_{th} in NGC 6946 is one order of magnitude smaller than that of the magnetic field E_{magn} (similar to the results for the Milky Way by Boulares & Cox 1990), i.e. the ISM is a low-β plasma. However, $\beta = E_{th}/E_{magn}$ may be underestimated if there is a contribution of hot gas or if the filling factor f_V of the diffuse ionized gas is larger than the assumed 5% (because $\langle n_{\rm e}\rangle \propto (I_{th} f_V)^{0.5}$).

In the inner parts of NGC 6946 the energy densities of the total magnetic field and turbulent gas motion are similar (Fig. 2), but the field dominates in the outer parts due to the large radial scale length of the total field energy ($\simeq$8 kpc), compared to the scale length of about 3 kpc for the neutral density. This seems to be in conflict with turbulent generation of interstellar magnetic fields. Radial diffusion of the magnetic field (Priklonsky et al. 2000), field connections through the wind-driven halo (Breitschwerdt et al. 2002), or a supra-equipartition turbulent dynamo (Belyanin et al. 1993) are possible explanations.

NGC 6946 rotates with $v_{\rm rot} \simeq 170$ km/s so that the rotational energy density of the neutral gas is $\simeq 500\times$ larger than that of the turbulent motion. However, in the outermost parts of galaxies the magnetic field energy density may reach the level of global rotational gas motion and affect the rotation curve, as

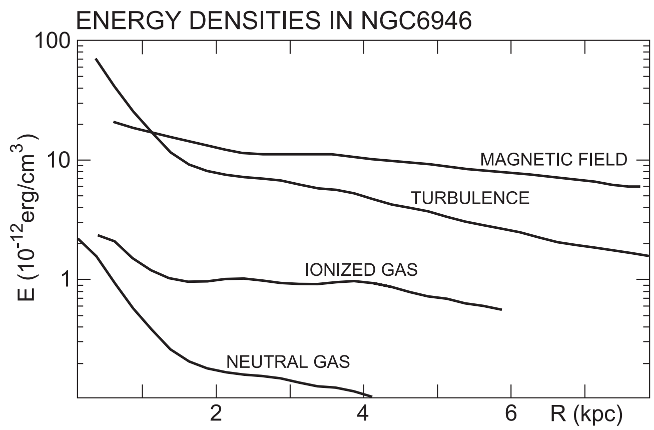

Figure 2. Energy densities and their radial variations in the spiral galaxy NGC 6946.

proposed by Battaner & Florido (2000). Field strengths in the outer parts of galaxies can be measured by Faraday rotation of polarized background sources. Han et al. (1998) found evidence for regular fields in M 31 at 25 kpc radius of similar strength as in the inner disk. More detailed studies in a number of galaxies are required.

Magnetic fields seem to play a major and possibly even dominant role in ISM physics, affecting gas flows, cloud collisions and the formation of spiral arms. Strongly tangled fields may provide a source for gas heating by reconnection.

5. Large-scale field structures

The Sun is located between two spiral arms, the Sagittarius/Carina and the Perseus arms. The mean pitch angle of the spiral arms is $\simeq -18°$ for the stars and $-13° \pm 1°$ for all gas components (Vallée 1995, 2002). Starlight polarization and pulsar RM data give a significantly smaller pitch angle ($-8° \pm 1°$) for the local magnetic field (Heiles 1996, Han & Qiao 1994, Indrani & Deshpande 1998, Han et al. 1999a). The local field may form a *magnetic arm* located between two optical arms, with a smaller pitch angle.

For external galaxies, maps of the total radio emission and ISOCAM maps of the mid-infrared dust emission reveal a surprisingly close connection (Frick et al. 2001b, Walsh et al. 2002). Strongest *total* fields generally coincide with highest emission from dust and gas in the spiral arms. This suggests a coupling of the tangled magnetic field to the warm dust mixed with cool gas. The *regular* field runs parallel to the spiral arms, though its ridge line is generally offset and, in some galaxies, forms *magnetic spiral arms* between the gaseous arms (Fig. 3) or across the arms, like in NGC 3627 (Soida et al. 2001). In galaxies

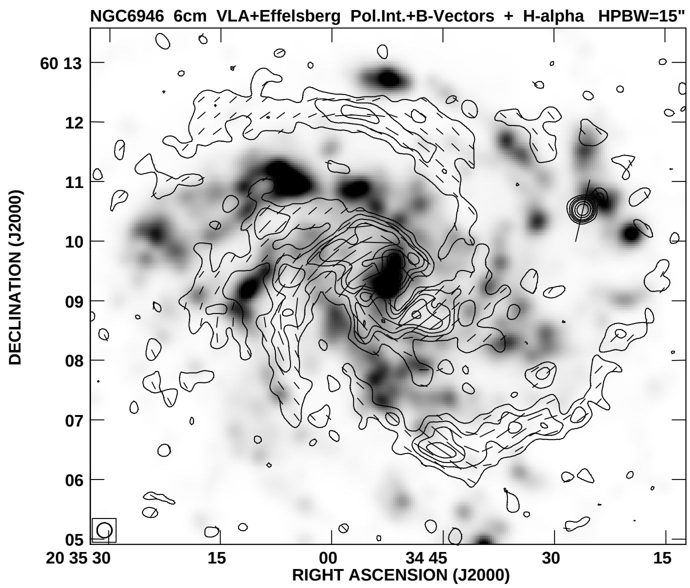

Figure 3. Polarized radio intensity (contours) and $\mathbf{B}$–vectors of polarized intensity of NGC 6946 at $15''$ resolution, combined from VLA and Effelsberg observations at $\lambda 6$ cm. The grey-scale image shows the Hα emission (kindly provided by A. Ferguson), smoothed to the same resolution. (From Beck & Hoernes 1996)

with strong density waves (like M 51) the regular field fills the whole interarm space, but is strongest at the positions of the dust lanes on the inner edge of the spiral arms (Fletcher, this volume). The low arm-interarm contrast is in conflict with classical 1-D shock compression and needs more sophisticated 3-D modelling (Martos & Cox 1998, Gómez & Cox, this volume).

The observation of large-scale patterns in Faraday rotation measures in the Milky Way and in external galaxies proves that a significant fraction of the field has a coherent direction and hence is not generated by compression or stretching in gas flows. The *dynamo* is able to generate and preserve coherent magnetic fields of spiral shape (Beck et al. 1996, Ferrière, this volume). Most observed field patterns require the superposition of several dynamo modes (Beck 2000).

A puzzling property of the Galactic magnetic field is the existence of several *reversals* (Rand & Lyne 1994, Vallée 1995, Han et al. 1999a, Frick et al. 2001a). To account for several reversals along Galactic radius, a *bisymmetric* magnetic spiral with a small pitch angle ($\simeq -7°$) has been proposed (Han & Qiao1994, Indrani & Deshpande 1998, Han et al. 2002).

It is striking that only very few field reversals have been detected in spiral galaxies. High-resolution maps of Faraday rotation, which measure the RMs

of the diffuse polarized synchrotron emission, are available for a couple of spiral galaxies. A dominating bisymmetric field structure was found only in M 81 (Krause et al. 1989). The disk fields of M 51 and NGC 4414 can be described by a mixture of dynamo modes which would appear like a reversal to an observer located within the disk (Berkhuijsen et al. 1997, Soida et al. 2002). In NGC 2997 a field reversal between the disk and the central region occurs at about 2 kpc radius (Han et al. 1999b). However, no multiple reversals along radius, like those in the Milky Way, were found so far in any external galaxy.

The discrepancy between Galactic and extragalactic data may be due to the different volumes traced by the observations. Results in the Galaxy are based on pulsar RMs which trace the warm ionized medium near the plane, while extragalactic RMs are averages over the whole thick disk. Some of the Galactic reversals may not be of galactic extent, but due to local field distortions or loops of the anisotropic turbulent field. Pulsar RMs around a star formation complex indeed revealed a field distortion which may mimic the reversal claimed to exist in the direction of the Perseus arm (Mitra et al. 2003). Many reversals on small scales are visible in the RM maps obtained from the diffuse Galactic synchrotron emission (Haverkorn et al. 2003a, 2003b). RM data at high frequencies are needed to obtain a clearer picture of the field structure.

6. Vertical fields

Edge-on galaxies possess thick radio disks (also called halos) of 1–3 kpc scale height (Lisenfeld & Dahlem, this volume), and the observed field orientations are mainly parallel to the disk (Dumke et al. 1995). A prominent exception is NGC 4631 with the brightest and largest halo observed so far, composed of vertical magnetic spurs connected to star-forming regions in the disk (Golla & Hummel 1994). NGC 5775 is an intermediate case with parallel and vertical field components (Tüllmann et al. 2000). The magnetic energy density in the halo of, e.g. M 83, exceeds that of the hot gas (Ehle et al. 1998), so that halo magnetic fields are important for the formation of a galactic wind. Magnetic reconnection is a possible heating source (Birk et al. 1998).

The vertical full equivalent thickness of the thick radio disk of the Milky Way is 3.0 ± 0.2 kpc near the Sun (Beuermann et al. 1985, scaled to a distance to the Galactic center of 8.5 kpc) which corresponds to an exponential scale height of $h_{\rm syn} \simeq 1.5$ kpc. In case of equipartition the scale height of the total field is $\simeq 4$ times larger than that of the synchrotron disk, i.e. $h_{B_{\rm t}} \simeq 6$ kpc. The local Galactic field is oriented mainly parallel to the plane, with a weak vertical component of $B_z \simeq 0.2\mu$G (Han & Qiao 1994).

Dynamo models predict the preferred generation of quadrupole fields where the toroidal component has the same sign above and below the plane. RMs of extragalactic sources and pulsars reveal no reversal near the plane for Galactic

longitudes $l = 90° - 270°$. Thus the local field is part of a large-scale symmetric (quadrupole) field structure. Towards the inner Galaxy ($l = 270° - 90°$) the signs are opposite above and below the plane. This may indicate a global anti-symmetric (dipole) mode in the inner Galaxy or in the halo (Han et al. 1997) with a poloidal field component perpendicular to the plane, which may explain the strong vertical fields observed near the Galactic center (see Sect. 2).

In external galaxies the vertical field symmetry could not be determined yet. A possible dominance of inward-directed radial field components may give evidence for preferred quadrupole-type fields (Krause & Beck 1998).

7. Small-scale field structures

Major progress in detecting small structures has been achieved with decimeter-wave polarization observations in the Milky Way (Duncan et al. 1997, 1999, Uyan"ker et al. 1998, 1999, 2003, Gaensler et al. 2001, Uyan"ker & Landecker 2002, Haverkorn et al. 2003a,b). A wealth of structures on pc and sub-pc scales has been discovered: filaments, canals, lenses, and rings. Their common property is to appear only in the maps of polarized intensity, but not in total intensity. The interpretation is hampered by several difficulties. Firstly, large-scale emission in Stokes parameters Q and U is missing in interferometric and even in single-dish maps so that the polarized intensities and angles can be distorted severely. Secondly, the wavelengths of these polarization surveys are rather long, so that strong depolarization of background emission in the foregound *Faraday screen* may lead to apparent structures like *Faraday ghosts* (Shukurov & Berkhuijsen 2003). On the other hand, such features carry valuable information about the turbulent ISM in the Faraday screen.

Another effect of Faraday depolarization is that, especially at decimeter wavelengths, only emission from nearby regions may be detected. The ISM is not always transparent for polarized radio waves, and the opacity varies strongly with wavelength and position. (This is why *polarization horizon* seems a less appropriate expression.) The wavelength dependence of Faraday depolarization allows *Faraday tomography* of different layers if maps at different (nearby) wavelengths are combined. More interesting results can be expected in this field.

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8. Discussion

Boulanger: The correlation between $B_{\rm t}$ and mid-IR emission measured by ISO: Isn't it a correlation between $B_{\rm t}$ and the power input from star formation rather than with cool gas?

Beck: Yes, there must be some physical interaction between magnetic fields and star formation which we don't understand yet. The correlation between radio continuum and Hα emission is much worse than between radio and mid-IR. A connection between magnetic fields and gas+dust clouds heated by star formation seems the most promising interpretation.

Rand: Is there evidence for differing pitch angles of the fields between arm and interarm regions in external spirals?

Beck: Yes, the pitch angles of the field in NGC 6946 are smaller in the interarm regions ($\simeq 15^\circ$) than in the spiral arms ($\simeq 30^\circ$).

Franco: The north-south field reversal in the inner Galaxy may imply that there is a neutral (current) sheet near the plane.

Beck: The regular field becomes weak towards the plane due to strong field tangling so that a neutral sheet will probably not develop.

Mac Low: If we see turbulent field, something must be tangling it. Magnetic tension straightens field lines if nothing opposes it. This appears to contradict the observation that field energy exceeds turbulent energy.

Beck: The *total* field dominates in the outer parts of NGC 6946, not the turbulent field. As the polarized emission decreases more slowly with radius than the unpolarized emission, the regular field becomes more important far out. Furthermore, the unpolarized synchrotron emission traces the unresolved field, consisting of field tangled on relatively large scales (though still unresolved by the telescope beam) and field which is really turbulent on small scales. Hence,

the energy of the turbulent field makes only some fraction of the total field energy and does not necessarily exceed the turbulent energy of the gas.

Gómez: What if the B-field is too tangled, weaved on itself, knotted? You could have a dominanting fluctuating field that does not need a constant driving.

Mac Low: A knotted field is very unlikely.